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(54) **Torque improvement in reluctance machines**

(57) A method and apparatus for increasing the starting torque of a two-phase switched reluctance motor is disclosed. The method involves the use of a specially constructed rotor position transducer with two sensing devices, each associated with one phase winding of the two-phase motor. The signals from the rotor position transducer are provided to a motor controller that energises each winding whenever energisation of the winding will produce torque in the desired direction.

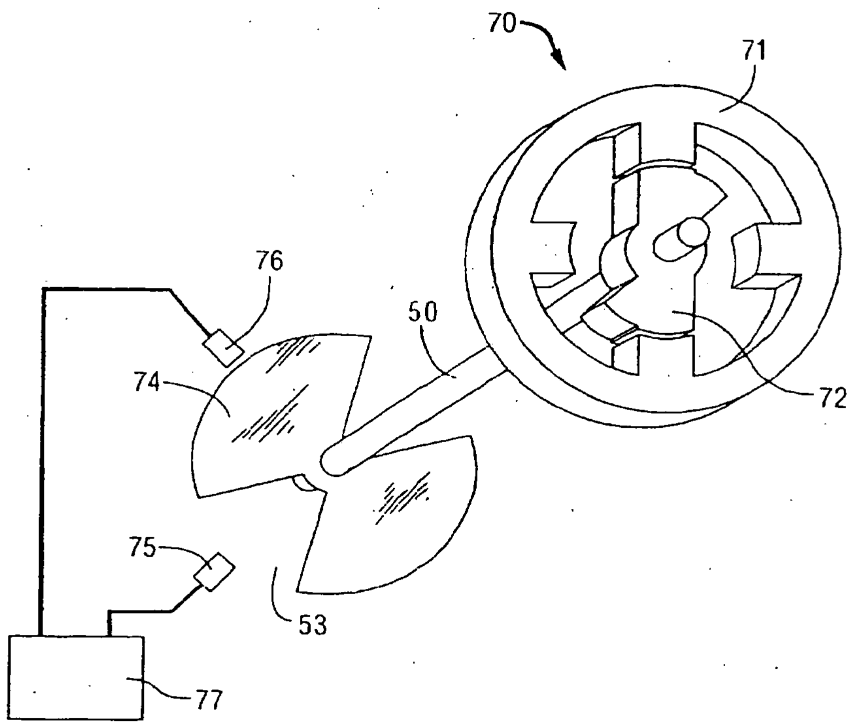

FIG. 7

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Description

This invention relates to reluctance machines and more particularly to switched reluctance motors. In particular, the present invention relates to a method and apparatus for increasing the starting and running torque of a two-phase switched reluctance motor.

In general, a reluctance machine is an electric motor in which torque is produced by the tendency of its movable part to move into a position where the reluctance of a magnetic circuit is minimized, i.e. the inductance of the exciting winding is maximized.

In one type of reluctance motor the energisation of the phase windings occurs at a controlled frequency. These motors are generally referred to as synchronous reluctance motors. In a second type of reluctance motor, circuitry is provided for detecting the angular position of the rotor and energising the phase windings as a function of the rotor's position. This second type of reluctance motor is generally known as a switched reluctance motor.

Figure 1 illustrates an exemplary switched reluctance motor having a stator 10 including six stator poles 11-16. Positioned within the bore formed by the stator and the inwardly pointing stator poles 11-16 is a rotor 18 which is mounted on bearings and is free to rotate. The rotor 18 has a number of outwardly extending projections 19 which form the rotor poles.

Associated with each stator pole is a wound coil of wire 17. In the illustrated motor, the coils of opposing stator poles are coupled together to form three phases: Phase A (coils from poles 11 and 14); Phase B (coils from poles 12 and 15); and Phase C (coils from poles 13 and 16). In the example illustrated in Figure 1, when Phase A is energised, electric current will flow through its coils such that stator pole 11 becomes, say, an inward-pointing electro-magnet of positive polarity and stator pole 14 becomes an electro-magnet of negative polarity. These electromagnets will produce a force of attraction between the energised stator poles and the rotor poles which will produce a torque.

By switching energisation from one phase to another, the desired torque may be maintained regardless of the angular position of the rotor. By switching the energisation of the phase windings to develop positive torque, the motor may be operated as a motor; by energising the phase windings to develop a retarding torque the motor may be operated as a brake or generator.

Figure 2 generally illustrates torque profiles for the three phases of the motor illustrated in Figure 1 over three hundred and sixty degrees of rotor rotation. The torque profiles have been simplified for clarity of explanation. Torque profile 20 generally illustrates the torque profile of Phase A of the motor illustrated in Figure 1 that would result if a constant current is passed through the winding coils positioned about stator poles 11 and 14 as a function of the rotor's angular position. As indicated in Figure 2, there is an initial rotor position 21 when the rotor poles are completely unaligned with the stator poles 11 and 14. In this position, the energisation of the phase winding for Phase A produces no torque. When the rotor is moved from this initial position, a positive torque is exerted on the rotor. As indicated by line 20 in Figure 2, as the rotor's position nears the stator pole, the torque produced by the energised winding around the stator pole increases. The torque will continue to increase until just after the rotor and stator poles begin to overlap and will thereafter decrease. When the rotor and stator poles are completely aligned, for example at position 22, the torque will drop to zero. As the rotor's position continues to change with respect to the stator pole, negative torque will be produced until the rotor is again completely unaligned with the stator pole, for example at point 23, where the produced torque again becomes zero. As Figure 2 indicates, the torque profile corresponding to the rotor's rotation from 180 to 360 degrees is identical to the 0-180 torque profile but offset 180 degrees.

Because the rotor and stator poles are regularly placed around the rotor and stator in the example of Figure 1, the torque profiles for the other two phases are the same as that for Phase A, but are displaced by 60 degrees. In Figure 2, the torque profile for Phase B is represented by line 24 and the torque profile for Phase C is illustrated by line 25. In general, for a reluctance machine with rotor and stator poles arranged in a symmetric fashion, the torque profiles of all phases will be the same but displaced $360/(N_r * p)$ where N_r is the number of rotor poles and p is the number of phases.

In many motor applications it is desirable to be able to energise the motor such that it produces a relatively high torque. Such a desired constant torque is illustrated by the line T_D in Figure 2. Referring again to Figure 2, it may be noted that, for any given rotor position there is always a phase that can be energised to give positive torque near the desired torque T_D. For example, if the rotor is at position 26, Phase A can be energised to provide a torque near the desired torque T_D. If the rotor is at position 27, Phase B can be energised to give a torque near T_D; and if the rotor is at position 28, Phase C can be energised to produce a torque close to the desired torque T_D.

In addition to having the capability of providing a relatively high torque T_D, regardless of rotor position, the reluctance motor of Figure 1 is also capable of providing a relatively constant, continuous torque, by always energising the winding that produces the torque most near the desired torque T_D. In general, for any reluctance motor having three or more phases, it is always possible to energise a winding and produce a torque at or near a desired constant torque T_D.

Typical two-phase reluctance motors, unlike the motor illustrated in Figure 1, are not capable of producing a relatively high desired torque T_D at all possible rotor positions. This is because, for two-phase motors, the

regions of positive torque for the different phases do not significantly overlap. This is generally illustrated in Figures 3 and 4.

Figure 3 generally illustrates a typical two-phase reluctance motor. The two-phase motor includes a stator 30 having four stator poles 31-34, around which coils 17 are placed. Opposite coils are connected to form two phase windings: Phase A, comprising the coil from poles 32 and 34, and Phase B comprising the coils around poles 31 and 33. The motor also includes a rotor 35 having two rotor poles. In the motor illustrated in Figure 3, the rotor 35 is constructed such that a "stepped air-gap" 36 is provided at each rotor pole. As those skilled in the art will recognize, the introduction of the stepped air-gap 36 "stretches" the positive region of the torque profile for each phase of the motor. This renders the torque profile of each phase of the motor asymmetrical in that the region of positive torque extends over a larger angle than the region of negative torque. This asymmetrical torque profile provides a slight overlap between the positive torque regions of the two-phases and ensures that, for any rotor position, it is possible to generate positive torque. The use of stepped air-gaps allows for starting of a two-phase motor at any rotor position. The use of stepped-air gap rotors for two-phase reluctance motors is generally known in the art and is discussed, for example, in El-Khazendar & Stephenson, *Proceedings of the ICEM* Munich (1986).

Figure 4 generally illustrates the torque profile for the two-phase motor of Figure 3 over one hundred and eighty degrees of rotation when a constant current flows through the motor windings. Line 41 generally illustrates the torque profile for Phase A and line 42 generally illustrates the torque profile for Phase B. As illustrated, the use of the stepped air-gap rotor stretches the torque profiles of the two-phases such that there are overlap regions, near points 43 and 43', where the produced torque from both phases is positive. Points 43 and 43' represent the points where the two torque profiles cross.

In known two-phase switched reluctance motors, a rotor position transducer (RPT) with a single position sensor, such as a Hall-effect device, an optical device or capacitive or magnetically based device, is used to control the energisation of the windings. A single sensor device is used because the two phase windings are each energised one-half of the electrical cycle. Thus, when the output of the single sensor is one level (e.g., a logic one) the first phase winding is energised. When the output of the single sensor changes to the opposite logic level (e.g., logic zero) the first phase winding is de-energised and the second phase winding is energised. Under this approach, the energisation of the two phase windings is mutually exclusive and the time duration of the single sensor's logic one is substantially equal to the time duration of the sensor's logic zero output. Typically, the points at which one phase winding is de-energised and the other energised is the point at which' the torque profiles of the two-phases cross (i.e., points 43 and 43' in Figure 4).

Figures 5 and 6 illustrate an RPT typical of the type used with known two-phase switched reluctance motors. In the typical configuration, a shaft 50 is coupled to the rotor 35 of a two-phase switched reluctance motor. Coupled to the shaft 50, so that it rotates with the shaft, is a vane 51 that has two different regions: mark regions 52 and space regions 53. A sensing element 54 is positioned at a location sufficiently near the shaft to sense whether it is near a mark or space region of the vane. In known two-phase switched reluctance motors, each mark and space region of the vane is substantially equal, with each being generally defined by an angular extent of approximately ($180/N_r$) degrees, where N_r is the number of rotor poles.

In operation, the sensing element 54 produces a first signal of one logic value (e.g., a high voltage or logic "1") when a mark region of the vane is located near the sensing element 54 and produces a second signal of a different logic level (e.g., a low voltage or logic "0") when a space region of the vane is located near the sensor. As those skilled in the art will recognize, when a vane 51 having say, two equal mark/space regions is utilized, over each 180 degree rotation of the rotor the sensing device 54 will produce a logic "1" signal over half of the rotation and a logic "0" signal over the other half of the rotation. This is generally illustrated in Figure 6A, where the output of the sensing device 54 is shown to be a logic "1" as the rotor rotates from the position defined as 0 degrees to the position defined as 90 degrees, and a logic "0" as the rotor rotates from the 90 degree position to the 180 degree position. Since the construction of the vane is symmetric, the signal repeats over the period of rotation from 180 degrees to 360 degrees.

In known two-phase switched reluctance motors, since each phase winding is energised mutually exclusively of the other, the output from the single sensing device 54 can be used to control the energisation of the motor. For example, during the interval when the output of sensor 54 is logic "1", one phase winding, e.g., Phase A, is normally energised and Phase B de-energised. During the interval over which the output of sensing device 54 is logic "0" the other phase winding, Phase B in this example, is energised and Phase A is de-energised. This is generally illustrated in Figures 6B and 6C. As those skilled in the art will recognize, the electronics required to convert the output of sensing device 54 into a switching signal for the phase windings are straightforward and can be constructed at low cost.

There are a number of types of vanes 51 and sensing devices 54 that are used in switched reluctance motors. For example, vane 51 can comprise a disk with light transmissive and light blocking elements that define the mark and space regions, and sensing device 54 can comprise a sensor with a light source and a light detector where the mark regions of the vane 51 interrupt the light beam from the source to the detector. For the light transmissive/light blocking vanes it is sometimes desirable to

slightly adjust the angular extent of the mark regions to compensate for the finite width of the light beam so that sensor 54 produces logic high and logic low signals of equal duration. As another example, vane 51 can include mark regions of ferromagnetic material and sensing device 54 can comprise a Hall-effect device that produces a first logic signal when the sensor is in the presence of the ferromagnetic signal and a second logic signal otherwise. For the type of sensing device illustrated in Figure 5, it is known to adjust the angular extent of the mark region to compensate for the proximity effect of flux fringing in the air adjacent to the ferromagnetic vane. The adjustment is made so that the sensor 54 produces logic high and logic low signals of equal duration.

For typical two-phase motors, such as the motor of Figure 3, there exists a rotor position, near points 43 and 43' in Figure 4, where the torque that the motor is capable of producing is relatively low. In many two-phase motors, the torque at this low point can be 30% or less of the maximum torque that the motor can produce. This low torque point can cause problems in that it can be difficult to start the motor if the rotor comes to rest at a position near the positions represented by points 43 and 43'. Additionally, when the motor is running, the low torque point results in significant variations in the torque output of the motor. These variations in torque output, referred to as torque ripples, are generally undesirable.

One known method of increasing the starting torque of the motor and decreasing the amount of torque ripple, is to profile the magnitude of the current applied to the phase windings such that the current flowing through the phase winding (and therefore the produced torque) is greater at points 43 and 43' than it would otherwise be. This approach is undesirable because it not only requires relatively complex control circuitry that offsets the low-cost, simple design advantages that make two-phase reluctance motors desirable, but also requires a considerable up-rating of the power converter to handle the increased current.

The present invention provides a method and apparatus for increasing the starting torque of two-phase reluctance motors and for decreasing the torque ripple in two-phase machines without profiling the current in the phase windings and without increasing the current rating of the switches in the power converter.

The present invention is defined in the accompanying independent claims. Preferred features are recited in the dependent claims.

The present invention is generally directed to a method of operating a two-phase switched reluctance motor to produce increased and smoother torque, where the motor includes a rotor, a first phase winding and a second phase winding, by energising both phase windings simultaneously during part of each rotational period of the rotor.

In one embodiment of the present invention, a control system for controlling two-phase switched reluctance motors is provided to produce torque in a desired direction. The control system includes a first rotor position transducer that produces a signal of a first level whenever energisation of the first phase winding will produce torque in the desired direction, a second rotor position transducer that produces a signal of the first level whenever energisation of the second phase winding will produce torque in the desired direction. The control system also includes a first switching device electrically coupled to the first rotor position transducer for energising the first phase winding whenever the signal produced by the first rotor position transducer is of the first level and a second switching device electrically coupled to the second rotor position transducer for energising the second phase winding whenever the signal produced by the second rotor position transducer is of the first level.

A still further embodiment of the present invention includes a switched reluctance motor system comprising a two-phase switched reluctance motor including a stator, a first phase winding, a second phase winding and a rotor. Associated with the motor are first and second rotor position transducer sensors for producing signals that respectively control the energisation of the first and second phase windings.

Yet another embodiment of the present invention provides a rotor position transducer assembly for a two-phase switched reluctance motor including a rotor, a shaft coupled to the rotor, a first phase winding and a second phase winding wherein the rotor and the phase windings are arranged to produce torque in a desired direction. The rotor position transducer assembly of this embodiment includes a first sensing device for producing signals to control the energisation of the first phase winding; a second sensing device for producing signals to control the energisation of the second phase winding; and a vane coupled to the shaft where the vane includes mark regions and space regions.

Other aspects and advantages of the present invention will become apparent upon reading the following detailed description of exemplary embodiments and upon reference to the drawings in which:

Figure 1 illustrates a typical three-phase reluctance motor having six stator poles and two rotor poles;
Figure 2 generally illustrates the torque profile for the three-phase reluctance motor of Figure 1;
Figure 3 illustrates a two-phase switched reluctance motor having four stator poles and a two pole, stepped-air gap rotor;
Figure 4 generally illustrates the torque profile for the two-phase reluctance motor of Figure 3;
Figure 5 generally illustrates an RPT of the type used in known switched reluctance motors;
Figures 6A-6C generally illustrate the output of the sensing device of the RPT of Figure 5 and the switching signals for the phase windings of the two-phase reluctance motor of Figure 3;
Figure 7 generally illustrates a two-phase switched

reluctance system constructed in accordance with the present invention;

Figure 8 schematically illustrates a controller that may be used in the present invention;

Figure 9A generally illustrates the torque profile of a two-phase switched reluctance motor that may be used in the present invention;

Figure 9B generally illustrates the available torque and switching signals for a switched reluctance motor system constructed in accordance with the present invention;

Figure 10 illustrates in greater detail the construction and positioning of the RPT of the present invention; and

Figure 11A-11D generally illustrate the generation of switching signals in response to the rotor's angular position in accordance with the present invention.

Similar reference characters indicate similar parts throughout the several views of the drawings.

In the present invention, a switching arrangement is provided for energising the phase windings of a two-phase switched reluctance motor such that the starting torque of the motor is increased and the torque ripple decreased. In the present invention, an RPT with two sensing head is used to control the energisation of the phase windings where each RPT sensing head independently controls the energisation and de-energisation of one of the phase windings. Moreover, in the present invention, each of the two RPT sensing heads is configured such that the phase winding corresponding to each RPT switches ON near the point that its energisation will produce positive torque and switches OFF when its torque drops near zero. In this switching scheme, there are periods during each complete rotation of the rotor in which both phase windings are energised at the same time. During these periods the torque produced by the energisation of the two windings is additive, resulting in a greater torque production than would be available if only a single phase winding were energised.

Figure 7 generally illustrates a two-phase switched reluctance motor system constructed in accordance with the present invention. The system generally includes a switched reluctance motor 70, including stator 71 and rotor 72 and an RPT comprising a specially configured vane 74 coupled to the motor shaft and two sensing devices 75 and 76. The outputs of the sensing devices 75 and 76 are provided to an electronic controller 77 that controls the energisation of the phase windings of motor 70.

The rotor 72 of the motor 70 in Figure 7 is a two-pole stepped air-gap rotor similar to that illustrated in Figure 3. The present invention is not limited to the use of stepped air-gap rotors, but applies to all two-phase reluctance motors in which each phase can produce positive torque for more than one-half of the rotor's angular rotation. The invention is applicable to stepped, graded or other forms of rotor.

The construction of the motor for use in the present invention may, except for the RPT, follow conventional switched reluctance motor construction methods. For example, the stator may be constructed of a number of stacked stator laminations having stator poles around which are wound the motor windings. The rotor may be constructed of a number of stacked rotor laminations affixed to a shaft. The construction of two-phase switched reluctance motors is generally understood and is not set forth in detail herein.

Unlike known two-phase motor systems, such as the one illustrated in Figure 5, the two-phase motor system of the present invention uses an RPT with two sensing devices 75 and 76 which are influenced by the same vane 74. In the present invention, each of the two sensing devices is associated with a different winding phase and each sensing device is configured and positioned to produce a first logic level signal (e.g., a logic high) when energisation of its associated phase winding will result in positive torque, and a second logic level signal (e.g., a logic low) at all other times.

The electronic controller 77 is also coupled to switching devices (not shown in Figure 7) that are coupled between the phase windings of the motor and a source of DC voltage.

Figure 8 schematically illustrates a simplified diagram of the controller 77 that may be used in the present invention. As illustrated in Figure 8, a source of DC voltage +V is provided across DC bus lines 80 and 81. Coupled across the DC bus lines 80 and 81 are the phase windings of the motor 70 schematically represented as inductances 82 (representing Phase A) and 83 (representing Phase B). Switching devices 84a and 85a couple the phase windings to the positive line and switching devices 84b and 85b couple the phase windings' to the negative or ground line 81 of the DC bus. The switching devices may be relays, power transistors, power MOSFETs, IGBTs, MOS controlled thyristors (MCTs) or the like. Return diodes 86a and 87a are coupled to the phase winding and the positive line 80 of the DC bus to provide a current path when the switching devices 84 and/or 85 are turned off and there is current still in the associated phase winding. Similarly, diodes 86b and 87b connect the phase winding to the lower DC bus line.

As illustrated in Figure 8, the controller 77 receives the output signals from the sensing devices 75 and 76 and generates switching signals to control the switching devices. In the simplified schematic of Figure 8, the electronic controller comprises signal conditioning circuits 88 and 89 that receive clean up and amplify the output signals from sensing devices 75 and 76 respectively to provide switching signals for the switching devices. In alternative embodiments the conditioning circuits 88 and 89 may be eliminated and the outputs from the sensing devices 75 and 76 used directly to control switching devices. In the exemplary schematic of Figure 8, the switching devices are such that a logic high output

from the sensing devices will produce a switching signal that turns on the appropriate switching devices and energises the phase winding associated with these devices. For example, if the output of the sensing device 75 is a logic high, the controller 77 will produce a signal that turns on the switching devices 84a and 84b, thus providing an electrical path between the positive bus line 80 and the ground bus line 81 through the phase winding 82. When the switching devices 84a and 84b are turned on, current will flow through the phase winding 82 until the switching devices 84a and 84b are turned off, at which time the current in the phase' winding 82 will decay through the path provided by the diodes 86a and 86b.

As those skilled in the art will recognize, the simplified controller 77 illustrated in Figure 8 is but one example of a controller that can be used in accordance with the present invention. The present invention is applicable to a large number of controllers and is not intended to be limited to the exemplary controller of Figure 8. For example, a more complicated controller could be used that controlled the current in the phase windings by chopping the voltage applied to the windings through controlled switching of the switching devices.

As discussed above, the present invention concerns the control of a two-phase switched reluctance motor such that the starting torque is increased and the torque ripple decreased. The way that these advantages are obtained in the present invention is explained generally by reference to Figures 9A and 9B.

Figure 9A illustrates in solid lines the torque profile for the two-phase motor of Figure 7 over 360 degrees of rotor rotation. Some of the details have been exaggerated to aid explanation. The line marked 90 represents the torque profile that will result if constant current is applied to the winding of Phase A and the line marked 91 illustrates the same information for Phase B. As illustrated, there is a point 93 where the positive torque produced by energisation of either Phase A or Phase B alone is relatively low. The inventor of the present invention has recognized that by energising the windings in accordance with the present invention it is possible to greatly increase the starting torque of a two-phase motor if it should stop at a position corresponding to position 93 and to decrease the torque' ripple. In particular, if the windings are energised independently of one another it is possible to effectively double the minimum torque and minimize the torque ripple. For example if each phase winding is energised near the time it starts to produce positive torque and de-energised near the time it begins to produce negative torque, there will be rotor positions for which both phase windings are energised. During these intervals, the torque produced by the two windings will be additive, resulting in increased torque production of the motor.

Figure 9B illustrates in a dashed line the torque profile that will result if the phase winding for Phase A is energised at point 94 (near the point where Phase A begins to produce positive torque) and de-energised at point 96 (near the point where Phase A begins to produce negative torque) and the phase winding for Phase B is energised at corresponding point 95 and de-energised at point 98. As the broken line indicates, during the interval when both phases are energised, the torque is additive and the produced torque will increase significantly, resulting in a much higher starting torque at point 93 and a much smaller torque ripple. It should be noted that the specific energisation and de-energisation positions illustrated in Figure 9B are not critical to the present invention. As long as there are time intervals during which both phase windings are energised and produce positive torque, it is possible to increase the starting torque of the motor and reduce torque ripple.

In order to implement the switching arrangement of the present invention, a specially configured and positioned RPT with two sensing devices may be used to control the energisation of the phase windings. Two sensing devices are necessary because a single sensing device is used to control independently the energisation of each phase winding. A specially configured RPT is necessary because the time duration of the logic high signal from each sensing device is required to be different from the time duration of its logic low signal. This is unlike known RPTs for two-phase motors. In the present invention, the specially configured RPT is used because, with stepped-gap motors, the ratio of duration of the positive torque region of the motor's torque curve to the negative torque region is greater than one. In the present invention, the RPT is configured and arranged such that one sensing device produces a first logic level signal (e.g., a logic 1) over the portion of the electrical cycle during which energisation of the phase winding associated with that device will produce positive torque on the rotor and a second logic level signal (e.g., logic zero) during the portion of the electrical cycle during which energisation of the phase winding associated with that device will produce negative torque on the rotor.

The lower portion of Figure 9B generally illustrates the desired outputs from an RPT that may be used in the present invention, though the absolute values of the angles used are exemplary. A first digital signal RPT_A represents a desired output for the sensing device associated with phase winding A. As illustrated in Figure 9B, the output of this sensing device is logic high over the portion of the rotor's rotation cycle during which positive torque is produced by the rotor when Phase A is energised and logic low at all other times. Similarly, the output of RPT_B is logic high when the torque produced by energising Phase B is positive and logic low at all other times. Notably, between points 95' and 96 (the point corresponding to the energisation of phase winding B and the de-energisation of phase winding A) the output of both sensing devices is high, since energisation of each phase will produce positive torque. In a like manner both windings will be energised between the points 97 and 98, 99 and 100, 101 and 102 and 94.

As discussed above, in the present invention the outputs of the RPT sensing devices are applied to the electronic controller 77 which uses the RPT outputs as switching signals to supply current to the appropriate windings. In the above example, the electronic controller 77 should supply current to the winding Phase A whenever the output of RPT_A is high and supply current to winding B whenever the output of RPT_B is high. The construction of electronic controllers that supply current to phase windings in a reluctance motor in response to RPT signals is known in the art and is not discussed in detail because the particular construction of the electronic controller is not essential to the present invention as long as current is applied according to the RPT signals as described above.

As Figure 9B illustrates, the ratio of the portion of the rotor's rotation cycle during which the output of a given RPT is logic high to the ratio over the portion of the rotor's rotation cycle during which it is low is not unity as is typical with known RPTs. Accordingly, specially configured RPTs must be used.

Figure 10 illustrates in greater detail one example of the RPT configuration of the present invention which is generally illustrated in Figure 7. Figure 10 generally illustrates the shape of vane 74 and the positioning of sensing devices 75 and 76.

In the embodiment of Figure 10, the sensing devices 75 and 76 are of the type that include a light source and a light detector. Accordingly, the vane 74 illustrated in Figure 10 comprises light transmissive portions 110 and 111 (the "space" portions of the vane) and light inhibiting portions 112 and 113 (the "mark" portions of the vane). Unlike the vanes used with known two-phase switched reluctance motors, the vane 74 constructed in accordance with the present invention has mark and space regions that are unequal.

The operation of RPTs using switching vanes and light detectors is well understood. Generally, a light beam is provided which passes from a light source to a detector. When the light beam is incident upon the detector, the detector produces a digital signal at a first logic level (e.g., a logic "0"). When the light beam is interrupted, for example by the passing of a vane between the beam source and the detector, the beam is not incident on the detector and the detector produces a digital output at a second logic level (e.g., a logic "1"). In the present example, the time interval when the detector produces a logic "1" signal is referred to as the "mark" period and the time interval over which the detector produced a logic "0" signal is referred to as the "space" period.

Referring back to Figure 10, it may be noted that the angular extent of the mark portions 112, 113 of the vane 74 vary significantly from the angular extent of the space portions 110, 111 of the vane. In this embodiment of the present invention, the vane 74 should be constructed such that the mark portions of the vane correspond directly to the positive torque regions of the torque profile. For example, referring to Figure 9B it may be noted that the positive torque region for Phase A extends over the region defined by the rotor's rotation from the 0 degree position to the 120 degree position and over the region defined by the rotor's rotation from the 180 degree position to the 300 degree position. Accordingly, the vane 74 has a first mark region 112 with an angular extent from a 0 degree position to a 120 degree position and a second mark region 113 with an angular extent from the 180 degree position to the 300 degree position.

The construction of rotor vane 74 in Figure 10 is exemplary only. As those skilled in the art will recognize, the present invention is applicable to other two-phase motors having different torque profiles with different regions of positive torque and to two-phase motors with different numbers of poles. In general, however, the mark regions of the vane should correspond to the positive torque regions of a given phase of the motor. In practice, the positive torque producing region for a given motor can be calculated experimentally or, preferably, determined empirically by examination of the motor. Each phase winding can be energised and the rotor can be rotated from the position corresponding to 0 mechanical degrees to 360 mechanical degrees while the resulting torque is measured through the use of known torque-measuring techniques.

As the above indicates, once the positive torque producing regions of the phase windings are known, the construction of the appropriate vane is fairly straightforward. The positive torque producing region for a given phase is determined and the mark regions of the rotor are then sized to correspond to the positive torque regions. After the mark and space regions of the vane have been determined, the RPT vane may be constructed using known cutting and manufacturing techniques.

As those skilled in the art will recognize and as generally discussed above, to generate the appropriate' RPT signals, it is sometimes necessary to slightly increase the desired mark region to compensate for the fact that the light beam that is interrupted by the vane has a finite width. To the extent that beam width compensation is required, it should be added on to the vane after the mark/space regions have been determined in accordance with the present invention. When such modifications are made, the angular span of the mark region of the vane will generally, but not exactly, correspond to the positive torque producing region of the phase windings. A similar modification may be required for other types of sensing devices. In all cases, however, the aim is to produce RPT signals whose mark/space ratios correspond to the ratios of angular periods of positive and negative torque.

The positioning of the two sensing devices 75 and 76 in the present invention takes advantage of the fact that the placement of the rotor poles about the rotor is symmetric and that each rotor pole is offset from the next adjacent rotor pole by 180 mechanical degrees. When

a rotor having two symmetric rotor poles is used, the two sensing devices 75 and 76 should be positioned such that the angle formed by the two sensing devices 75 and 76 spans 90 mechanical degrees. This is illustrated in Figure 10 where the angle spanned by sensing devices 75 and 76 is 90 mechanical degrees.

When the RPT vane is properly constructed and the sensing devices properly positioned in accordance with the present invention, the appropriate switching signals will be generated. This is illustrated in Figures 11A-11D. As Figure 11A indicates, during the interval over which the rotor rotates from angular position represented by 0 degrees to the angular position represented by 30 degrees, the output of sense detector 75, and RPT_A, and the output of sense detector 76 and RPT_B, are both logic "1", resulting in the energisation of phase windings A and B. As the rotor continues to rotate from 30 degrees to 90 degrees the mark region of the vane will continue to block light from sense detector 75, resulting in a logic "1" RPT_A signal over this interval, and continued energisation of phase winding A. Over this same period there is nothing to block the light to sense detector 76 and the output RPT_B signal is a logic "0". This is illustrated in Figure 11B.

Figure 11C illustrates the rotor's rotation from 90 degrees through 120 degrees. During this period of rotation, the outputs of both RPT sensors are high and both phase windings are energised. Figure 11D illustrates the outputs for the rotor's rotation from 120 degrees to 180 degrees. During this interval, the output of RPT_A is a logic "0" and the output of RPT_B is a logic "1". Because the rotor is symmetrical, the RPT outputs for the region defined by 180 degrees to 360 degrees is a duplicate of the region defined by 0 degrees to 180 degrees. As explained above, the outputs of the RPT are applied to the electronic controller to control the switching of the phase windings.

The invention utilizes the overlapping angular region in which torque in the desired direction is available from both phases of a two-phase reluctance machine. To achieve this in at least a portion of the region in which torque is available both phases are energised simultaneously. While it is described above in relation to the full region in which torque is available from both phases, the skilled person will appreciate that a proportion of the region may be used for simultaneous energisation instead.

The invention is also applicable to reluctance' generators in which the applied input torque is translated into an output voltage. By simultaneous switching of the windings, according to the invention a smoother output voltage can be produced.

The skilled person will also be aware that reluctance machines can be arranged with the rotor embracing an inner stator. The invention is equally applicable to this construction as well. Similarly, the invention can be used in relation to linear reluctance motors in which the moving member travels across a sequentially energised stator track. The moving member in a linear reluctance motor is still often referred to as the rotor. The term "rotor" is intended to embrace such moving members in linear reluctance motors.

While the invention has been described in connection with the illustrative embodiments discussed above, those skilled in the art will recognized that many variations may be made without departing from the present invention. For example, the discussed examples utilized an RPT making use of a light sensor and a vane including light transmissive and light blocking regions. As those skilled in the art will be aware light reflecting and non-light reflecting regions could be used or other types of RPTs, including RPTs using Hall-effect or capacitive, inductive or magnetic-based devices and RPTs where the mark and space regions are reversed could be used without departing from the scope of the present invention. Moreover, the specific mark and space regions in the above example were provided for illustrative purposes only. It will be understood that different mark space regions can be used without departing from the present invention.

The above description of several embodiments is made by way of example and not for purposes of limitation. In particular, the invention is applicable to switched reluctance machines having numbers of stator and rotor poles different from those illustrated above. The present invention is intended to be limited only by the scope of the following claims.

Claims

1. A switched reluctance drive system comprising:

   a two-phase switched reluctance machine having a stator with stator poles, a rotor and phase windings' arranged in relation to the stator for energisation of the stator poles;
   switch means connected with each of the phase windings;
   position indicator means for producing signals indicative of the position of the rotor relative to the stator; and
   control means responsive to an input demand and to the said signals from the position indicator means to actuate the switch means to control the current in the phase windings; characterised in that
   the control means are also operable to actuate the switch means of both phases simultaneously when the rotor is in a position in which energisation of both phases will contribute to torque production in the same direction in accordance with the input demand.

2. A system as claimed in claim 1 in which the position indicator means comprise first position sensing

means arranged to produce turn-on and turn-off signals for the switch means in accordance with torque productive regions of the position of the rotor relative to the stator in the desired direction for one of the phases, and second position sensing means arranged to produce turn-on and turn-off signals in accordance with torque productive regions of the position of the rotor relative to the stator in the said desired direction for the other of the phases.

3. A system as claimed in claim 2 in which a sensor output influencing member is arranged to rotate with the rotor, the first and second position sensing means being arranged in relation to the said member to be influenced thereby.

4. A system as claimed in claim 3 in which the member is a vane defining first and second sensor output influencing regions, such that the sensing means produce a binary output corresponding to switch means turn-on and turn-off signals as the rotor rotates.

5. A system as claimed in claim 2, 3 or 4 in which the control means include a signal conditioning means for conditioning the output of the first position sensing means and a second signal conditioning means for conditioning the output of the second position sensing means, the outputs of the conditioning means being respectively operatively connected to actuate the switch means of the two phases.

6. A system as claimed in any preceding claim in which the rotor is a stepped air-gap rotor, having at least one radially outer pole face defining two arcuate surfaces relatively radially closer to and more spaced from the faces of the stator poles.

7. A system as claimed in any preceding claim in which the control means and the rotor position sensing means are arranged to run the switched reluctance machine as a motor.

8. A system as claimed in any of claims 1 to 6 in which the control means and the rotor position sensing means are arranged to run the switched reluctance machine as a generator.

9. A method of controlling the output of a two-phase switched reluctance machine having a rotor, a stator and at least one phase winding for each phase, comprising:

   sensing the position of the rotor relative to the stator;
   actuating switch means in accordance with the position of the rotor relative to the stator to energise the phase windings in sequence to produce an output; and
   further actuating the switch means in accordance with the position of the rotor relative to the stator to energise the phase windings simultaneously when the rotor is in a position in which energisation of both phases contributes to the output torque in a desired direction.

10. A method as claimed in claim 9, including sensing the position of the rotor relative to the stator poles associated with the at least one winding of one phase and separately sensing the position of the rotor relative to the stator poles associated with the at least one winding of the other phase.

11. A position transducer for a two-phase switched reluctance machine, having a stator with stator poles, a rotor and phase windings arranged in relation to the stator for energisation of the stator poles, the transducer comprising:

   first position indicator means for producing position signals indicative of the position of the rotor relative to the stator in which a desired direction of torque production is available from one of the phases;
   second position indicator means for producing position signals indicative of the position of the rotor relative to the stator in which the desired direction of torque production is available from the other of the phases;
   the first and second position indicator means being' arranged to produce signals indicative of rotor positions in which the desired direction of torque production is available from both phases simultaneously.

12. A transducer as claimed in claim 11 in which the first and second position indicator means share a member mountable to rotate with the rotor of the machine, each position indicator means having a sensor operable to produce the position signals under the influence of the member.

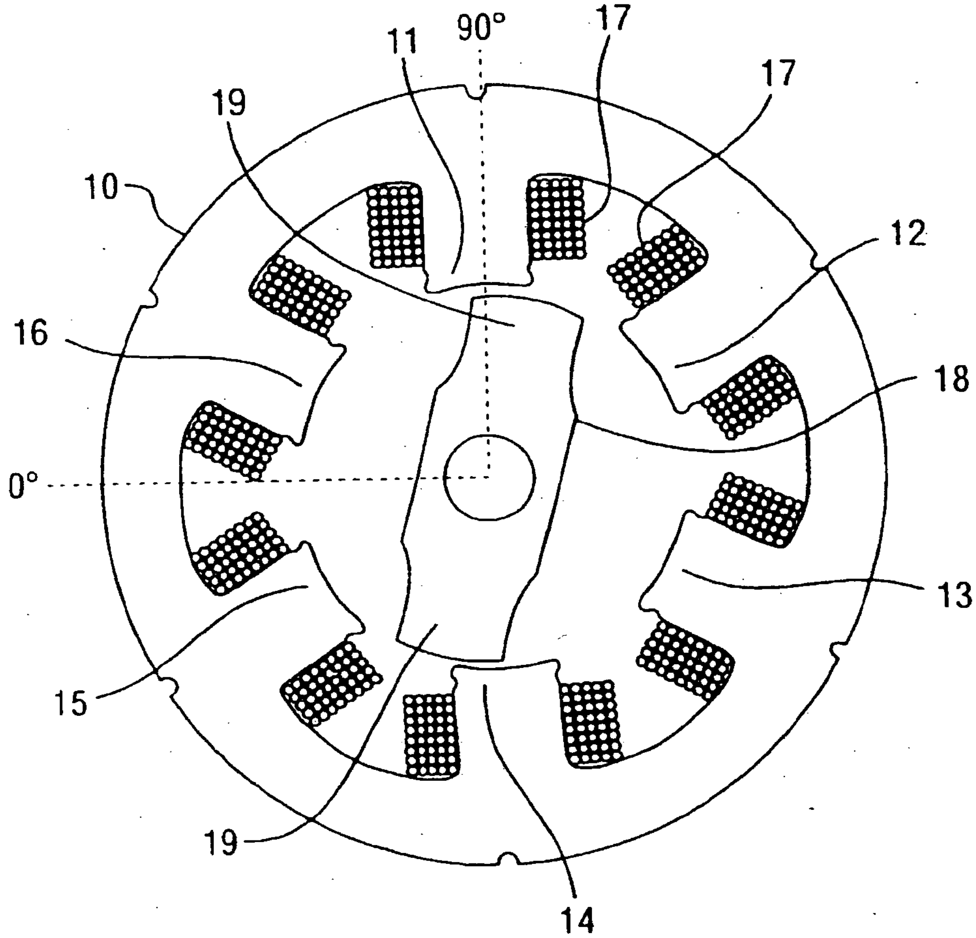


FIG. 1

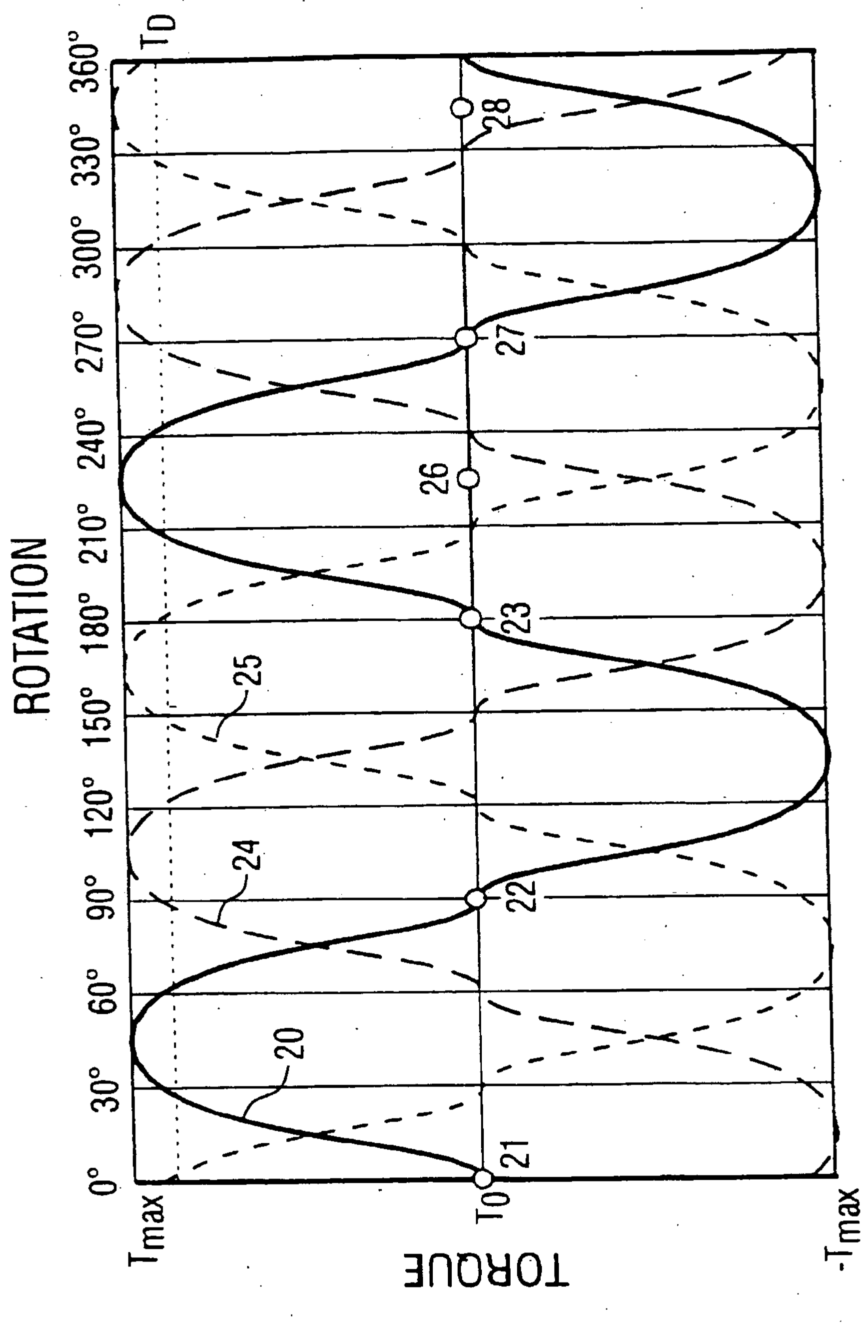

ROTATION
0°
30°
60°
90°
120°
150°
180°
210°
240°
270°
300°
330°
360°
TD
TORQUE
Tmax
T0
-Tmax
20
21
22
23
24
25
26
27
28

FIG. 2

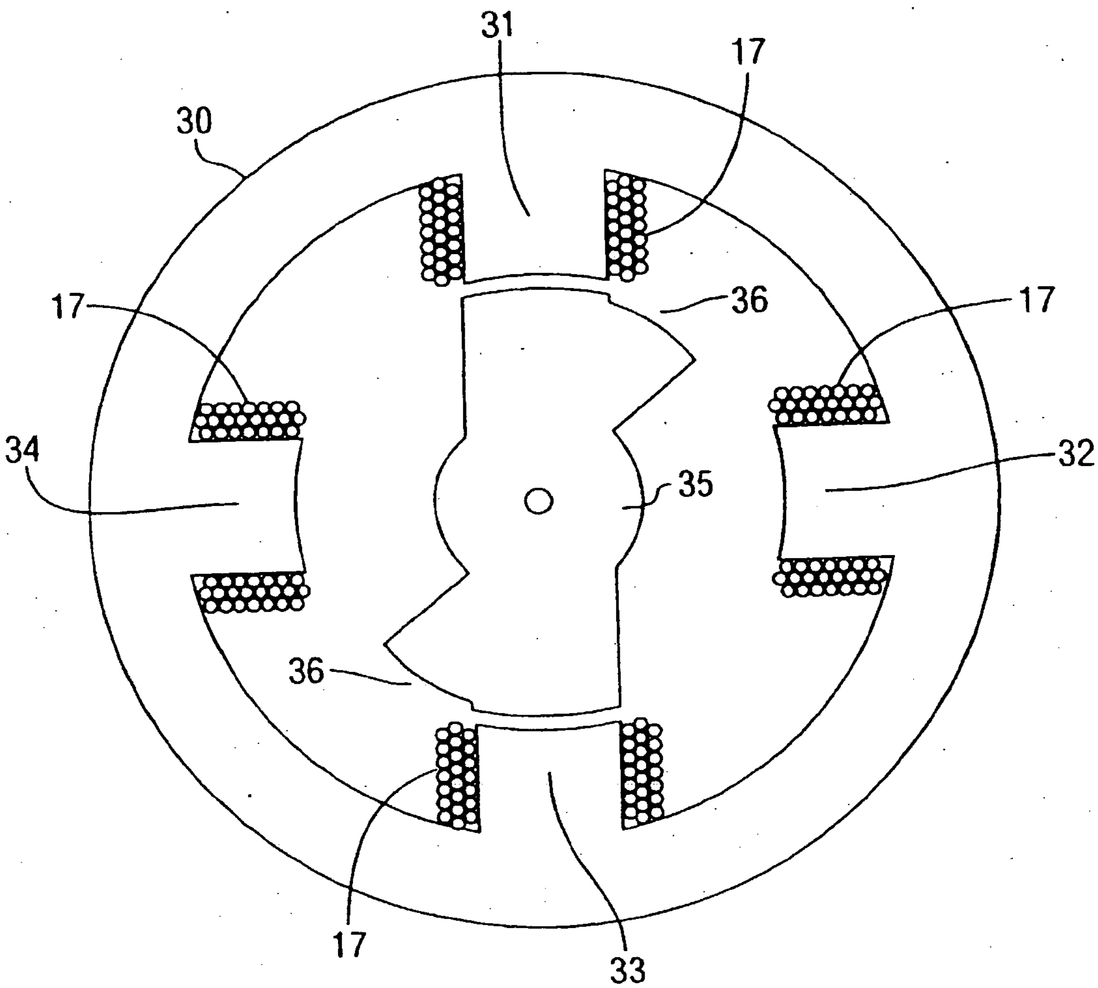
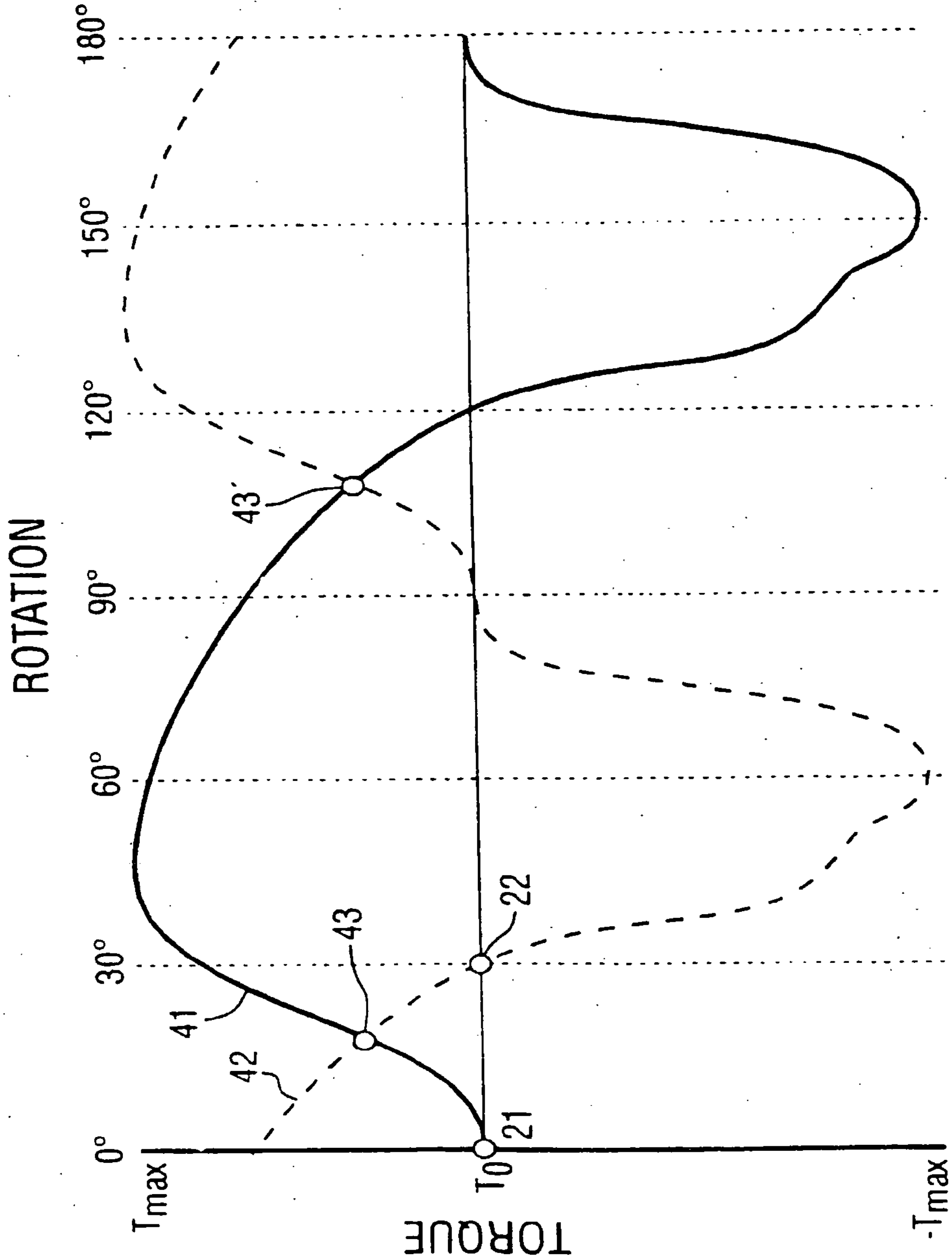


FIG. 3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0°
30°
60°
90°
120°
150°
180°
Tmax
T0
-Tmax
TORQUE
41
42
43
43'
22
21

FIG. 4

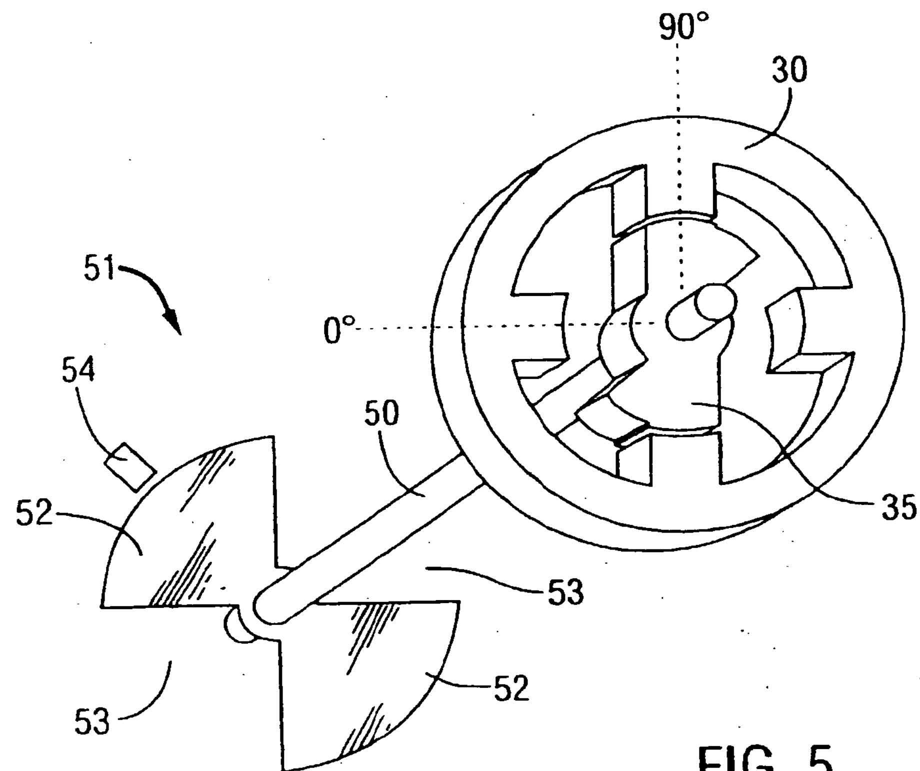


FIG. 5

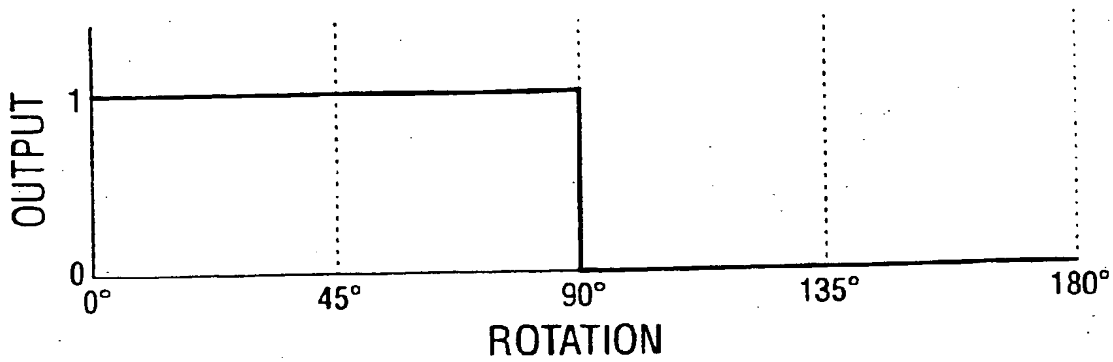


FIG. 6A

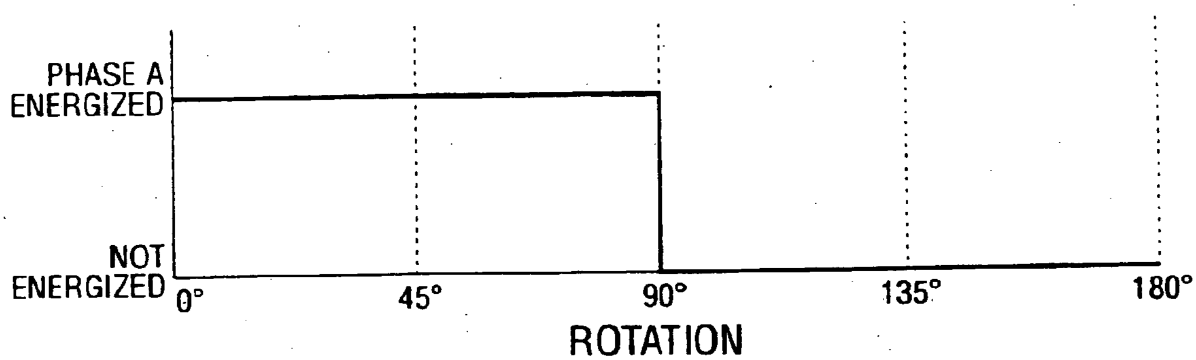


FIG. 6B

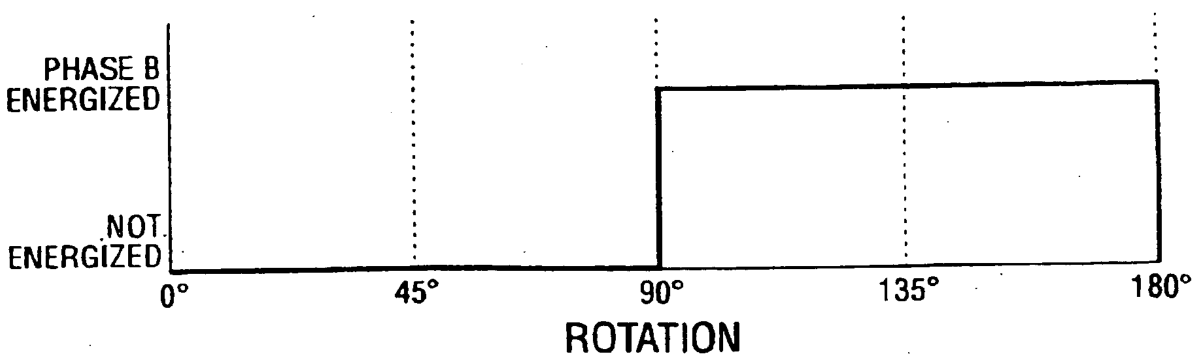


FIG. 6C

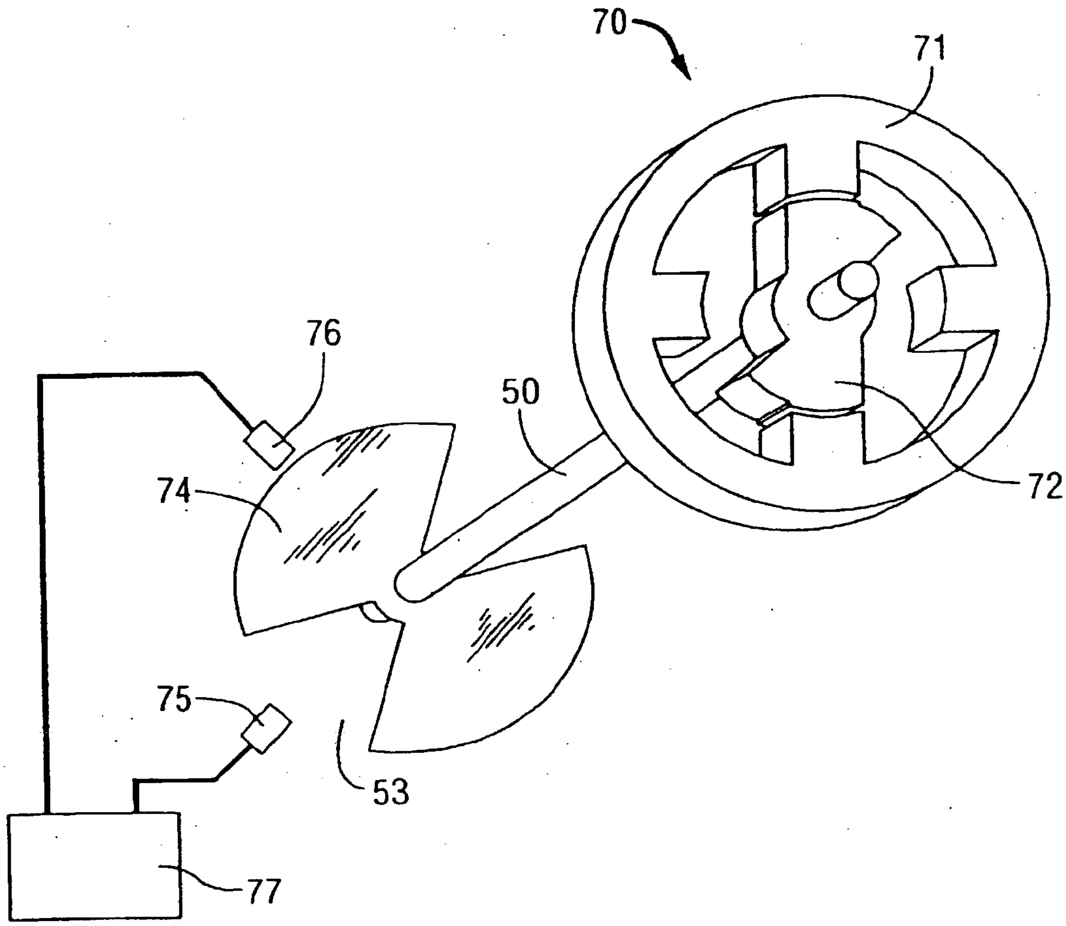


FIG. 7

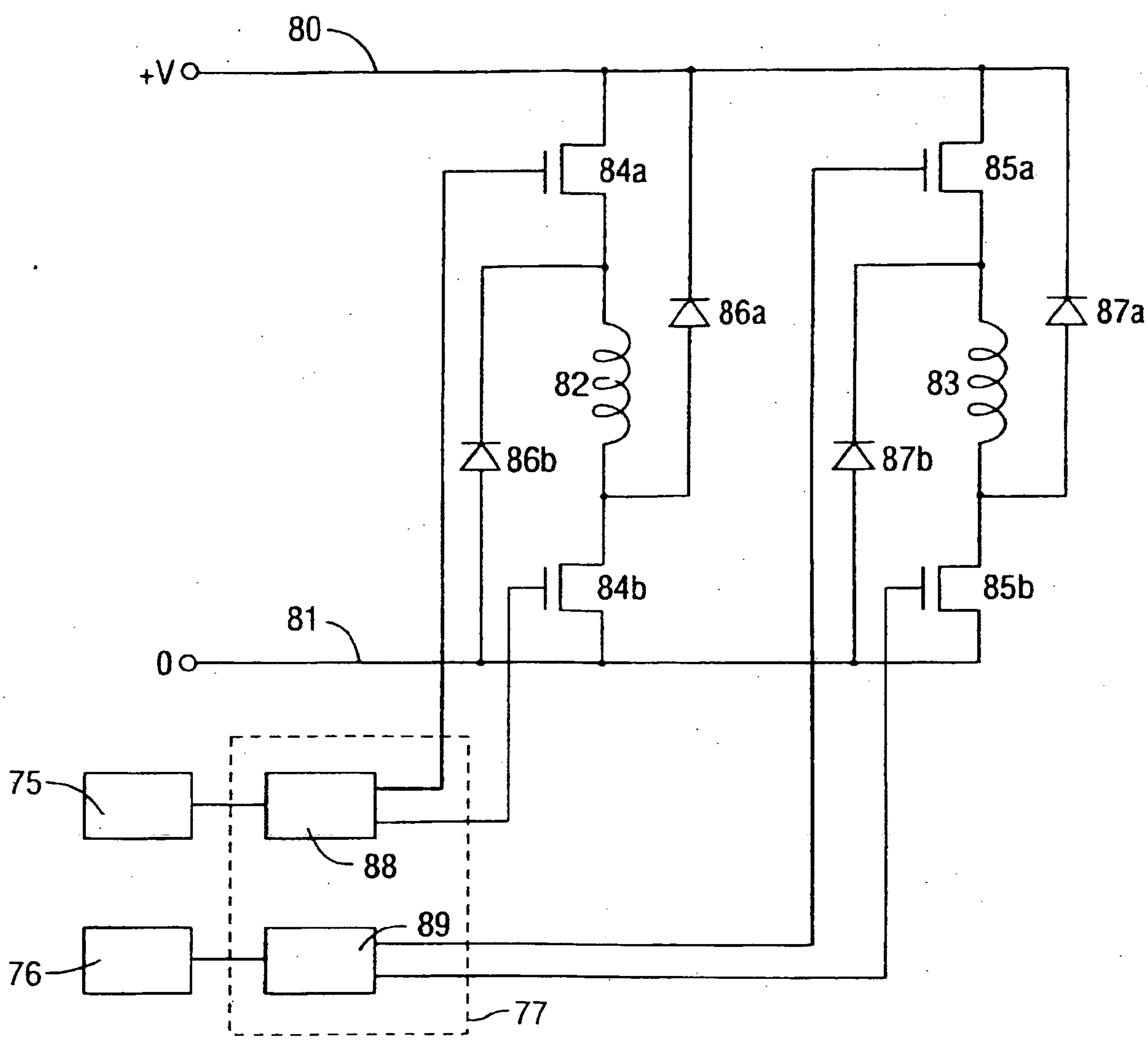


FIG. 8

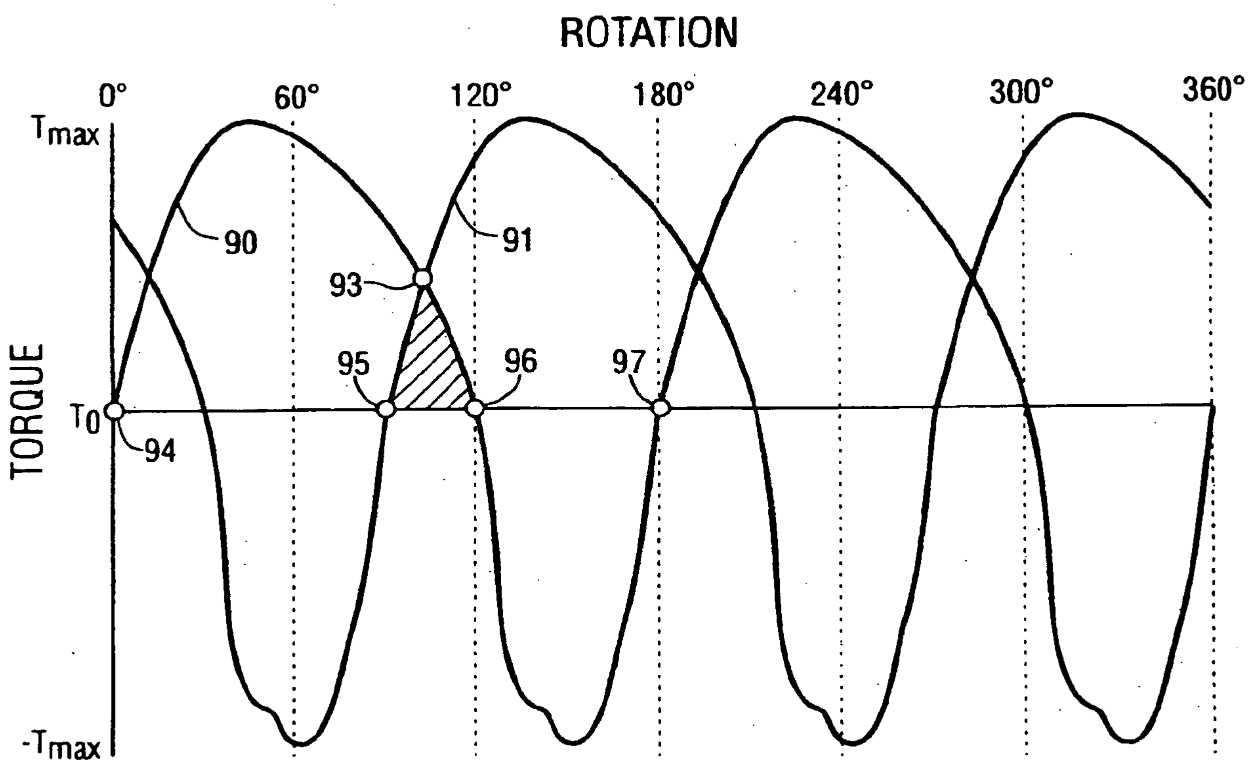
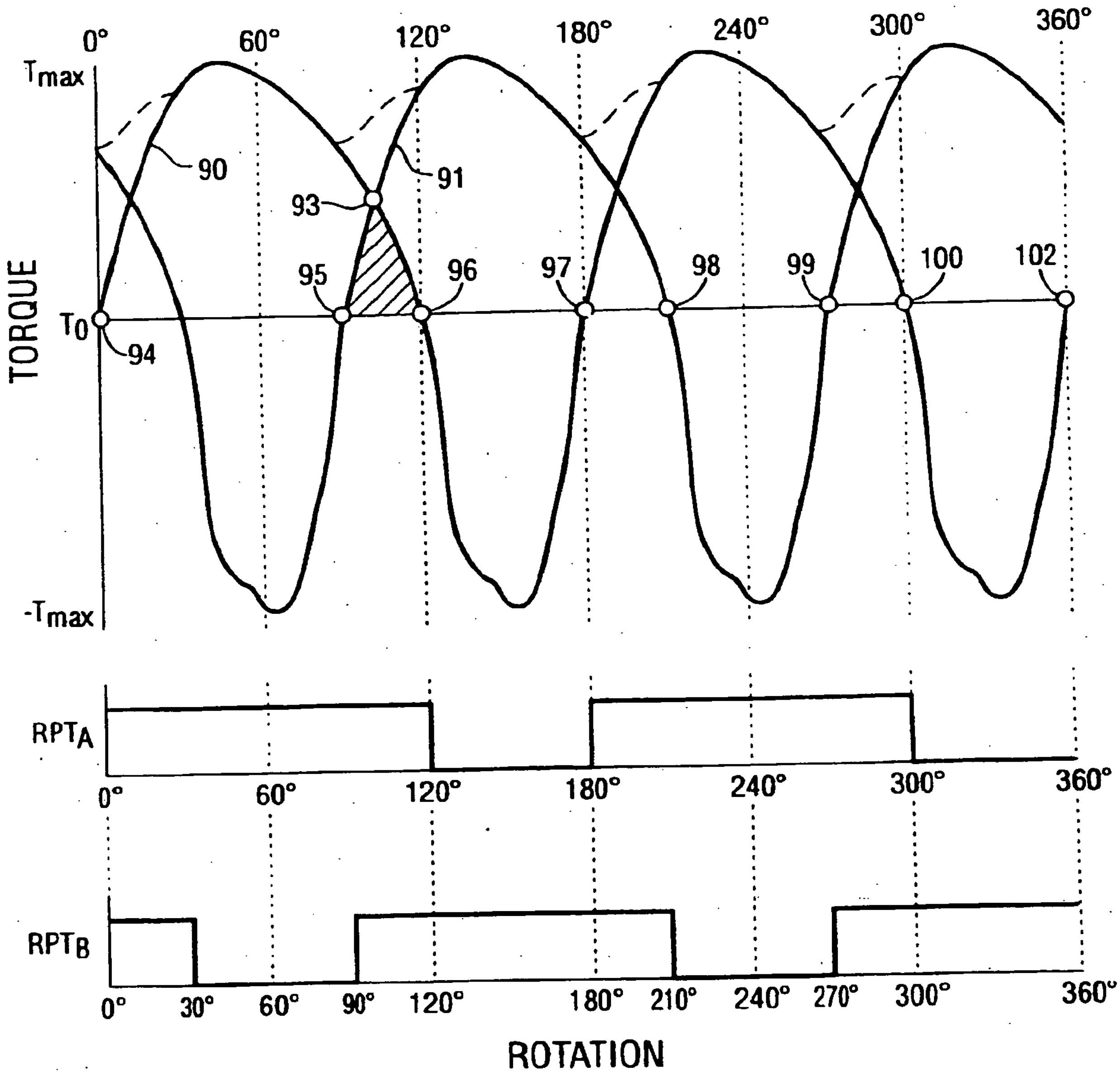

ROTATION
0°
60°
120°
180°
240°
300°
360°
Tmax
TORQUE
T0
-Tmax
90
91
93
94
95
96
97

FIG. 9A


0°
60°
120°
180°
240°
300°
360°
Tmax
-Tmax
TORQUE
T0
90
91
93
94
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96
97
98
99
100
102
RPTA
0°
60°
120°
180°
240°
300°
360°
RPTB
0°
30°
60°
90°
120°
180°
210°
240°
270°
300°
360°
ROTATION

FIG. 9B

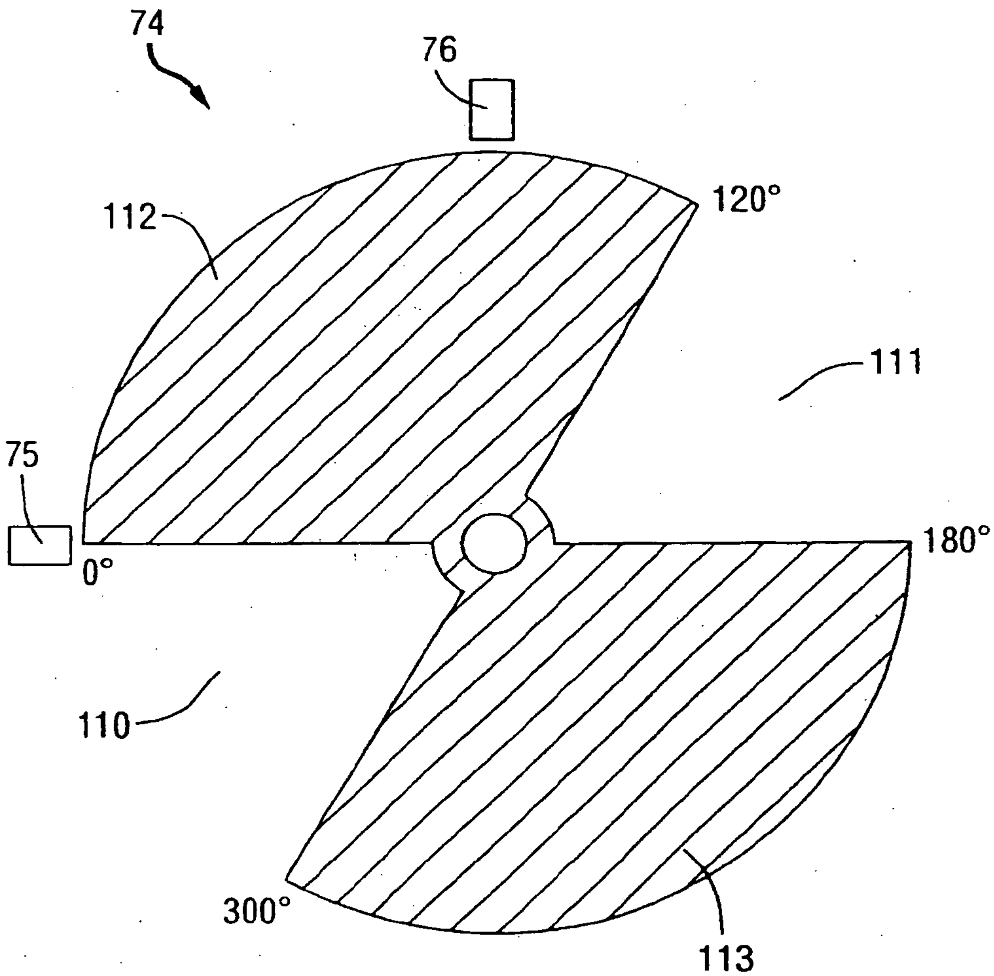
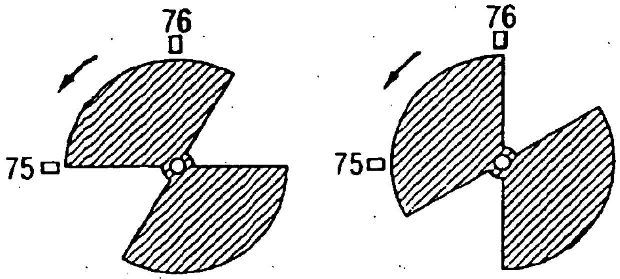


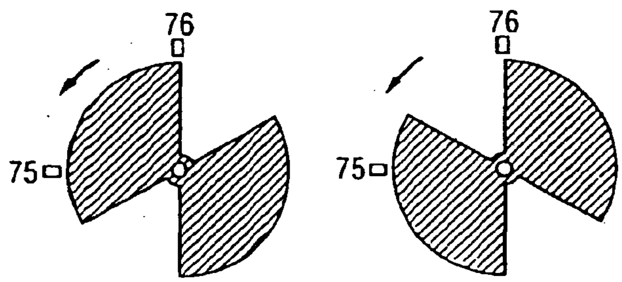
FIG. 10



0-30°

SENSE DETECTOR 75/RPT$_A$	SENSE DETECTOR 76/RPT$_B$
1	1

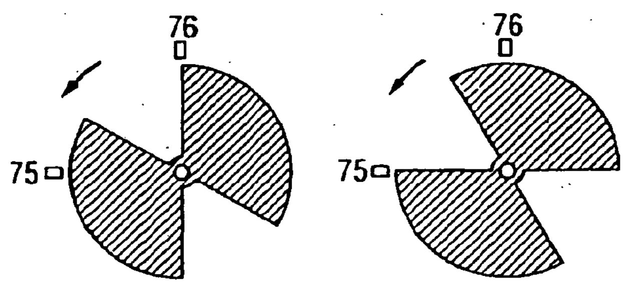
FIG. 11A



30-90°

SENSE DETECTOR 75/RPT$_A$	SENSE DETECTOR 76/RPT$_B$
1	0

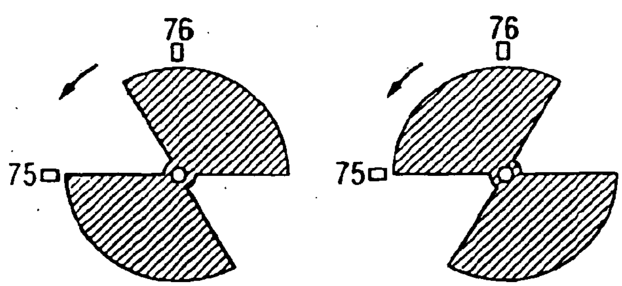
FIG. 11B



90-120°

SENSE DETECTOR 75/RPT$_A$	SENSE DETECTOR 76/RPT$_B$
1	1

FIG. 11C



120-180°

SENSE DETECTOR 75/RPT$_A$	SENSE DETECTOR 76/RPT$_B$
0	1

FIG. 11D

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(54) **Torque improvement in reluctance machines**

(57) A method and apparatus for increasing the starting torque of a two-phase switched reluctance motor is disclosed. The method involves the use of a specially constructed rotor position transducer with two sensing devices, each associated with one phase winding of the two-phase motor. The signals from the rotor position transducer are provided to a motor controller that energises each winding whenever energisation of the winding will produce torque in the desired direction.

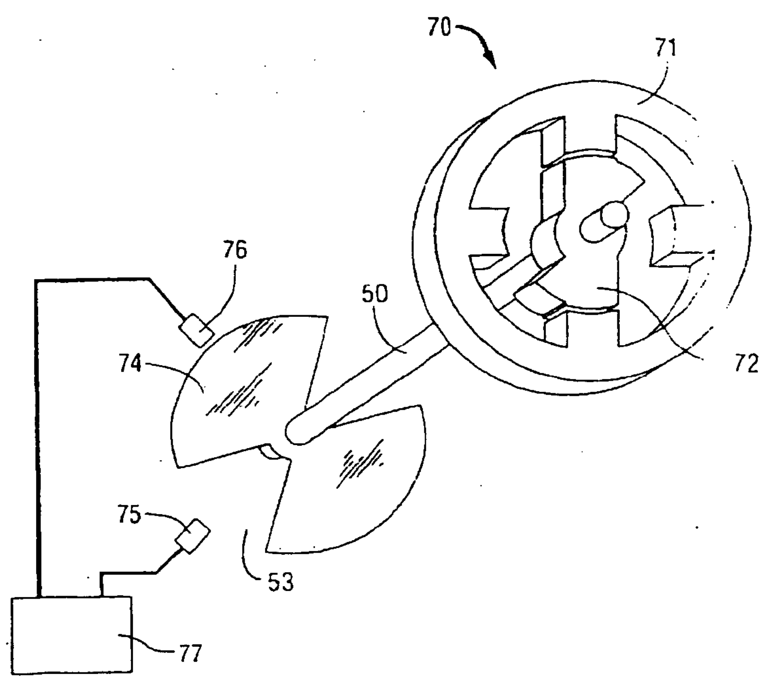

FIG. 7

EP 0 734 117 A3

European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 96301556.5

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl. 6)
A,D	EL-KHAZENDAR, M.A. et al. Analysis and optimisation of the 2-phase self-starting switched reluctance motor. Munich: Proceedings of the ICEM, 1986, pages 1031-1034, especially page 1031, left-hand column, lines 1-29, fig. 1,2.	1,6,7, 9,11	H 02 P 7/05
A	US 5355069 A (BAHN) 11 October 1994 (11.10.94), abstract, column 2, line 16 - column 3, line 6, column 4, line 58 - column 6, line 56, fig. 1-3.	1,7,9, 11	
A	US 4896089 A (KLIMAN et al.) 23 January 1990 (23.01.90), column 4, line 15 - column 6, line 17, fig. 1-3.	1,7,9, 11	TECHNICAL FIELDS SEARCHED (Int. Cl.6) H 02 P H 02 K

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
VIENNA	24-10-1997	HAJOS

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